

# LoopFest IX

*Radiative Corrections for the LHC and Lepton Colliders*

Top Quark Physics  
with  
D-Dimensional Generalized Unitarity

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in collaboration with K. Melnikov



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## Same title - New results

Last Loopfest:

- mainly technical aspects
- some benchmarks, numerical stability
- intermediate results

This time:

- almost no technical aspects
- more phenomenology

# Outline

- i.) NLO QCD corrections to  $t\bar{t}$  production and decay
- ii.) Top mass measurement at NLO QCD    [+ S. Biswas]
- iii.) NLO QCD corrections to  $t\bar{t} + \text{jet}$  production

**JHEP 0908:049,2009,**  
**arXiv: 1006.0910 [hep-ph],**  
**arXiv: 1004.3284 [hep-ph]**

# Is this really new?

No and Yes.

Literature on hadronic top production beyond leading-order is rich:

- **stable top quarks:**

**Classic NLO QCD corrections:**

Beenakker, Dawson, Ellis, Frixione, Meng, Nason, v. Neerven, Schuler, Smith; Czakon, Mitov

**Threshold resummation & Coulomb corrections:**

Banfi, Bonciani, Catani, Czakon, Frixione, Kidonakis, Kiyo, Kühn, Laenen, Mangano, Mitov, Moch, Nason, Ridolfi, Steinhouse, Sterman, Uwer, Vogt

**Electroweak corrections:**

Beenakker, Bernreuther, Fuecker, Denner, Hollik, Kao, Kollar, Kühn, Ladinsky, Mertig, Moretti, Nolten, Ross, Sack, Scharf, Si, Uwer, Wackerlo, Yuan

**NNLO QCD contributions:**

Anastasiou, Aybat, Bonciani, Czakon, Ferroglia, Gehrmann, Körner, Langenfeld, Maitre, Merebashvili, Mitov, Moch, Rogal, Studerus, Uwer

- **decays of top quarks:**

**Study of non-factorizable corrections:**

Beenakker, Berends, Chapovsky, Fadin, Khoze, Martin, Melnikov, Yakovlev

**Factorizable correction to top decays:**

Czarnecki, Jezabek, Kühn; Bernreuther, Brandenburg, Si, Uwer

**Spin correlations:**

Mahlon, Parke; Bernreuther, Brandenburg, Si, Uwer

- **event generators:**

**MC@NLO:** Frixione, Webber; Laenen, Motylinski, White

**POWHEG:** Alioli, Frixione, Nason, Oleari

## Is this really new?

No and Yes.

Only very recently:

NLO QCD corrections to  
top quark pair production and decay at hadron colliders

Bernreuther, Si; MCFM: Ellis, Campbell (2010); Melnikov, S. (2009)

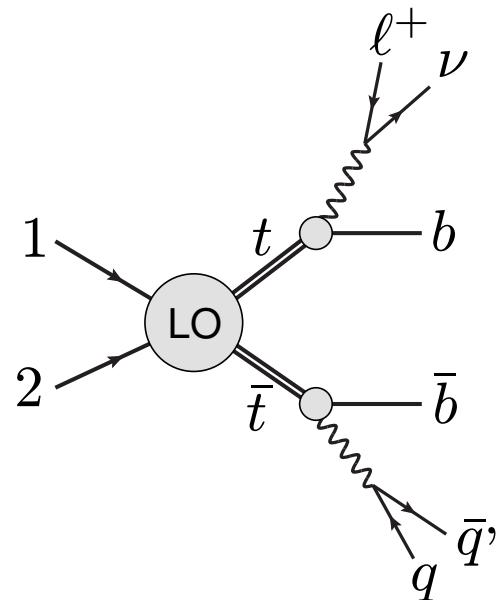
Top quark decays: leptonic or hadronic decays at NLO  
Narrow Width Approximation  $\Gamma_t/m_t \rightarrow 0$   
neglect non-factorizable corrections

Allows for:

- realistic description of the final state
- implementation of arbitrary detector cuts
- accounting for all spin correlations

# Our implementation

## leading order:

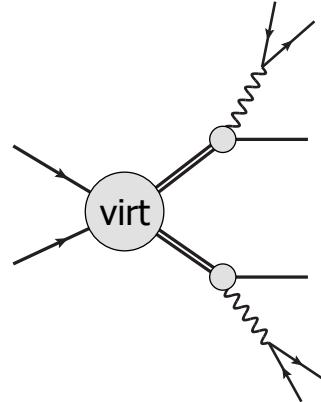


- Generate phase space of decay particles
- $\bar{u}(p_t) \rightarrow \tilde{u}(p_t) = \mathcal{M}(t \rightarrow b\ell^+\nu) \frac{i(p_t + m_t)}{\sqrt{2m_t\Gamma_t}}$
- $\mathcal{M}_{\text{tree}} = \tilde{u}(p_t) \tilde{\mathcal{M}}(12 \rightarrow \bar{t}t) \tilde{v}(p_{\bar{t}}) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$

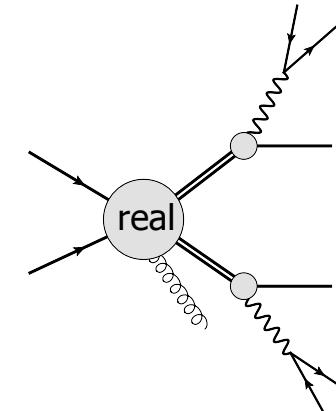
# Our implementation

Next-to-leading order:

Production



D-dimensional generalized unitarity  
+ OPP

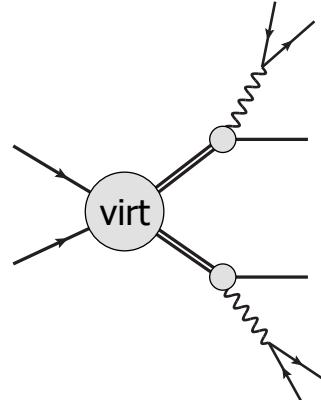


Dipole subtraction  
with alpha dependence

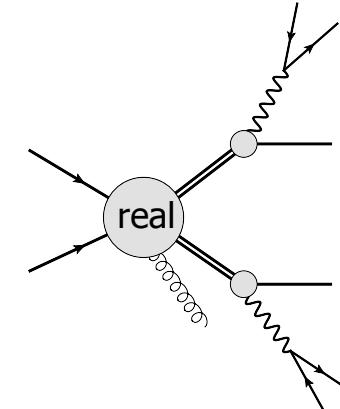
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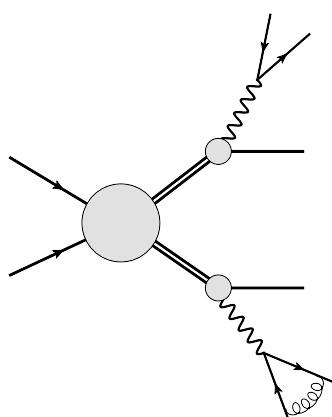
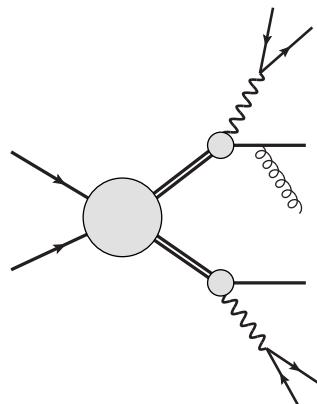


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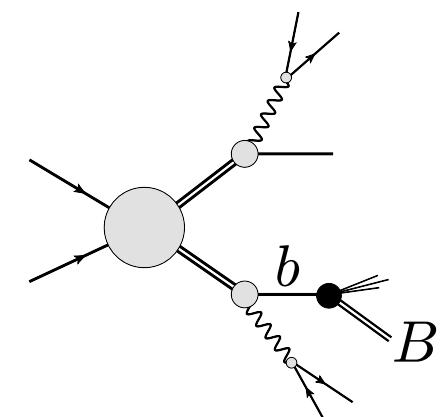


Dipole subtraction  
with alpha dependence

Decay



+ extra:



B-meson fragmentation

## How relevant is this?

- Measurement of the total  $t\bar{t}$  cross section

The total cross section is claimed to be measured with 5-10% accuracy  
 NLO QCD corrections: typically 10-30%

**Note:** The total cross section is never measured in an experiment

$$\sigma_{\text{tot}} = \frac{N_{\text{obs}}}{\mathcal{L}} \cdot \frac{1}{A}$$

with  $A = \frac{\sigma_{\text{cuts}}}{\sigma_{\text{tot}}}$

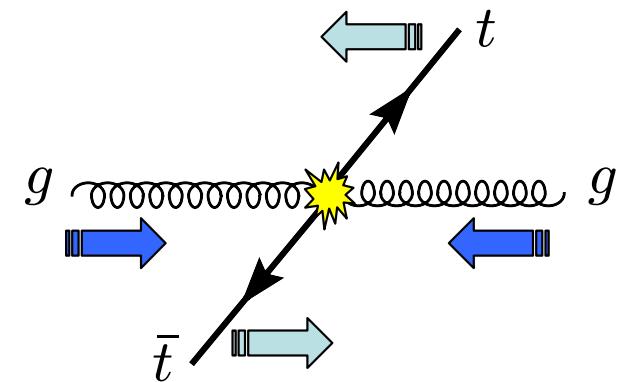
To claim that the total cross section has been measured with NLO accuracy,  
 we need to calculate  $A$  at NLO QCD. Otherwise, we introduce potential biases.

## How relevant is this?

- Spin correlations in  $t\bar{t}$

[Parke,Mahlon]

[Bernreuther,Brandenburg,Si,Uwer]

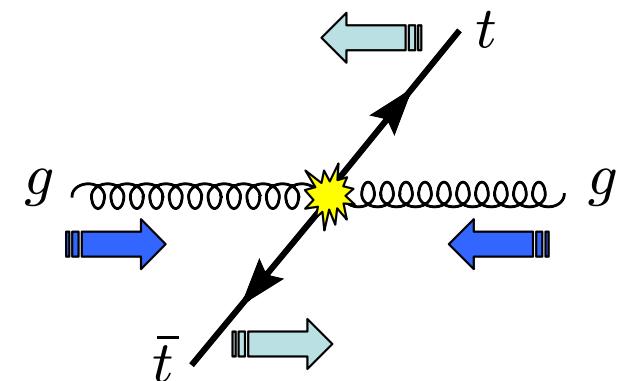


# How relevant is this?

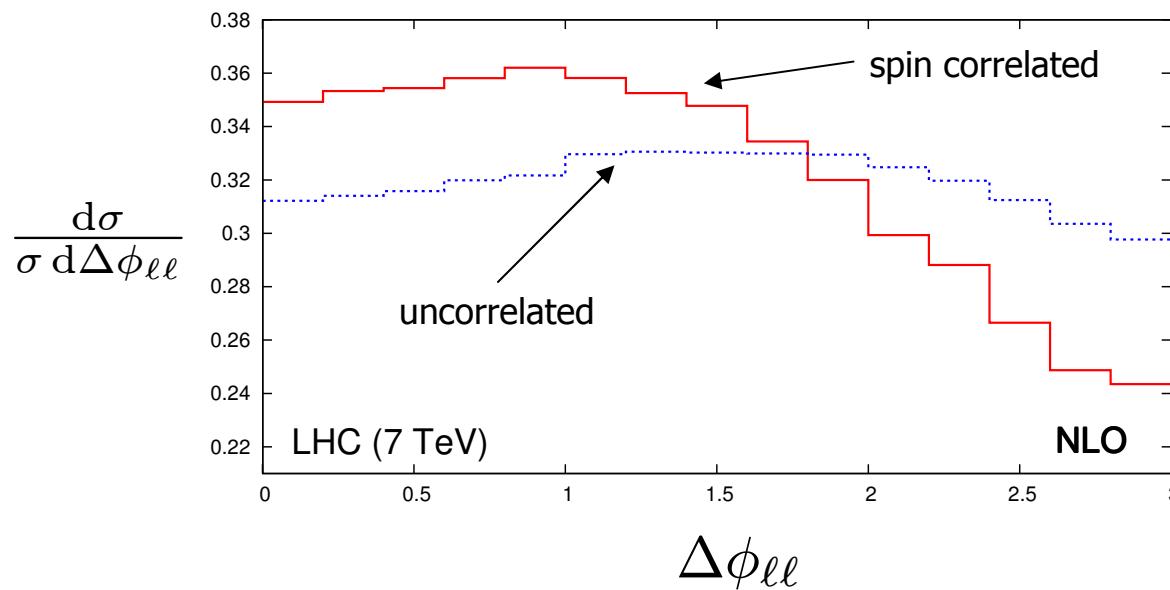
- Spin correlations in  $t\bar{t}$

[Parke,Mahlon]

[Bernreuther,Brandenburg,Si,Uwer]



Angle and invariant mass distributions are very sensitive to spin correlations



Cuts:

$$p_{T,\ell} > 20 \text{ GeV}$$

$$p_{T,\text{bjet}} > 25 \text{ GeV}$$

$$p_{T,\text{miss}} > 40 \text{ GeV}$$

$$\eta_\ell, \eta_{\text{bjet}} < 2.5$$

+  $m_{\ell\ell} < 100 \text{ GeV}$   
 $p_{T,\ell} < 50 \text{ GeV}$

## How relevant is this?

- Measurement of the top quark mass at the LHC

Target precision is about 1 GeV, dominated by systematics.

Clean measurements involve kinematics of top quark decay products.

So far, systematics of all those measurements were estimated by parton showers.

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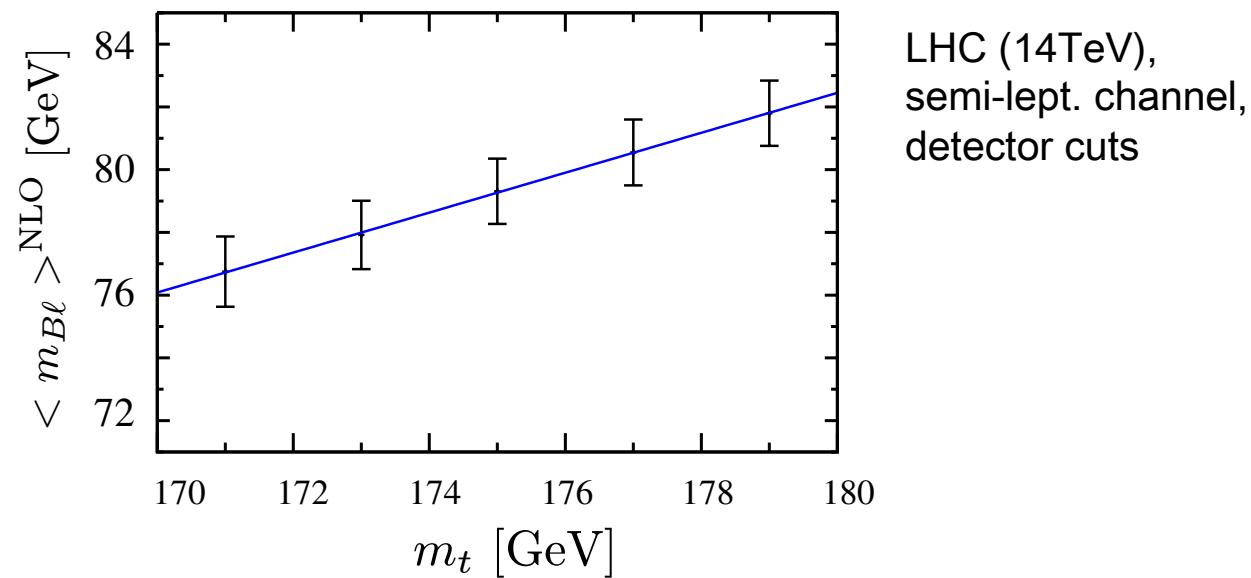
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One example:

average invariant mass  
of lepton and B-meson

⇒ uncertainty of 1.5 GeV  
is feasible with  $20 \text{ fb}^{-1}$

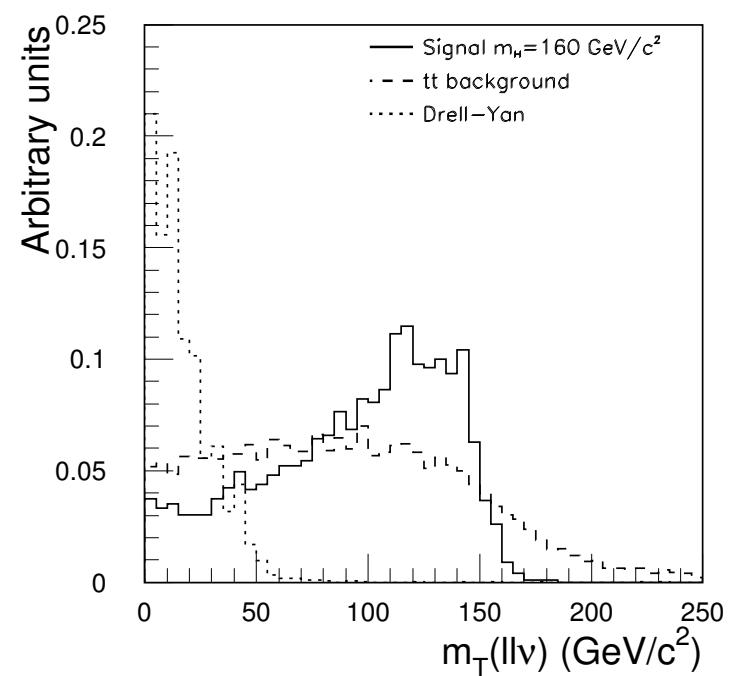
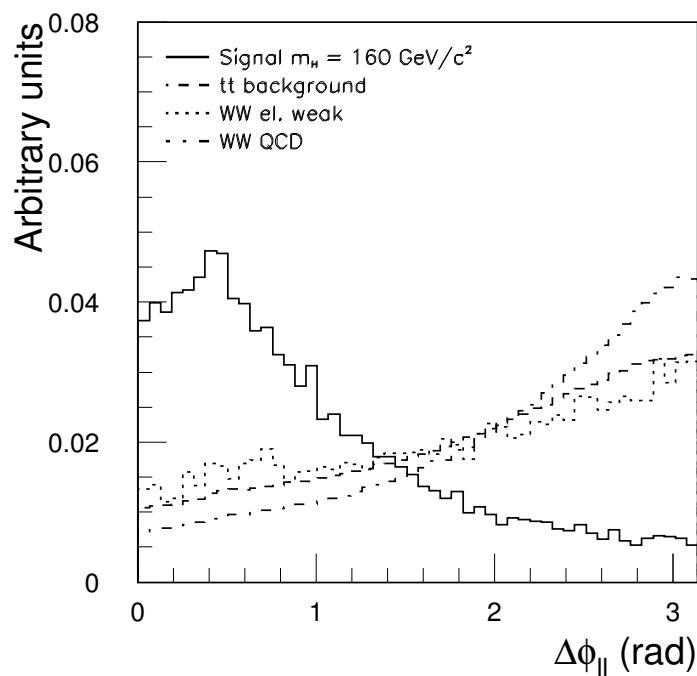


Process:  $t\bar{t}$  + jet

Major background for Higgs  $\rightarrow$  WW in VBF

$t\bar{t} + X$  comprises 2/3 of all backgrounds (80% from  $t\bar{t}$  + jet )

ATLAS:



## Process: $t\bar{t}$ + jet

LHC:	$\sigma_{\text{NLO}} = 376.2 \pm 0.6 \text{ pb}$	Dittmaier,Uwer,Weinzierl (2005)
	$\sigma_{\text{NLO}} = 376.6 \pm 0.6 \text{ pb}$	Bevilacqua,Czakon,Papadopoulos,Worek (2010)
	$\sigma_{\text{NLO}} = 375.8 \pm 1.0 \text{ pb}$	Melnikov,S. (2010)

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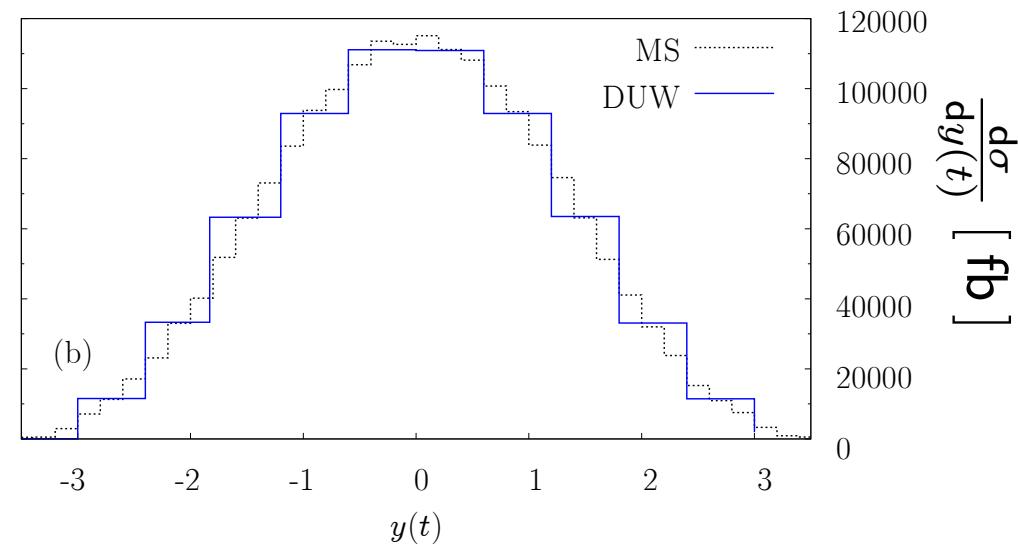
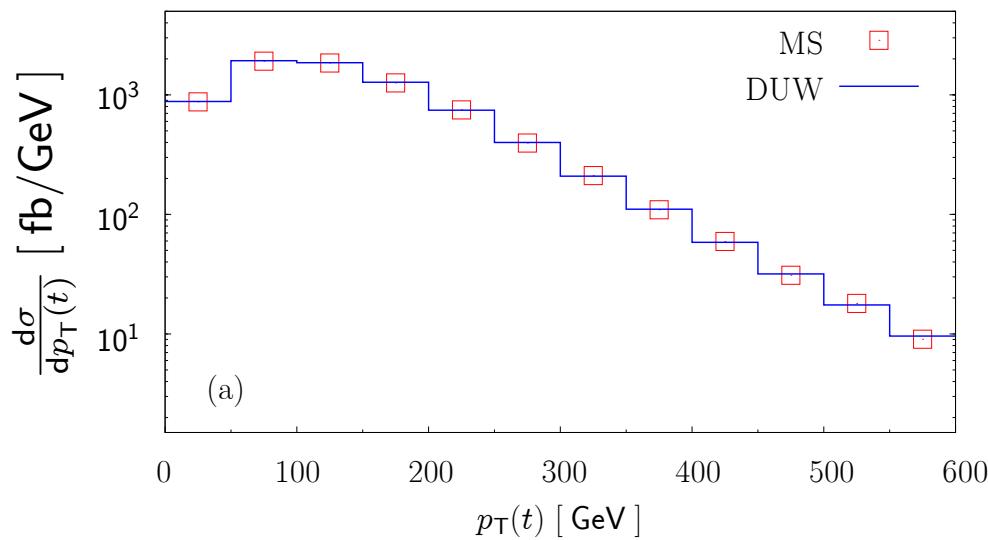
$\sigma_{\text{NLO}} = 376.6 \pm 0.6 \text{ pb}$

Bevilacqua,Czakon,Papadopoulos,Worek (2010)

$\sigma_{\text{NLO}} = 375.8 \pm 1.0 \text{ pb}$

Melnikov,S. (2010)

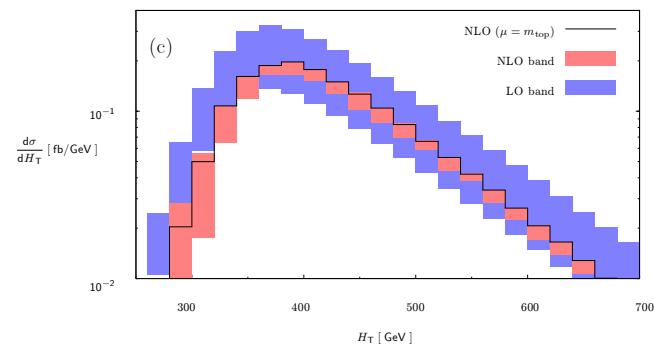
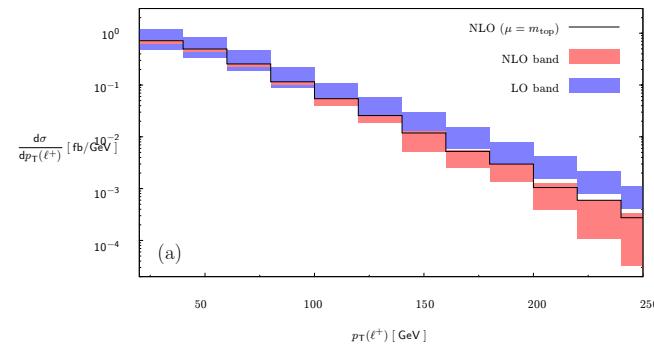
Cross check with DUW (stable top quarks):



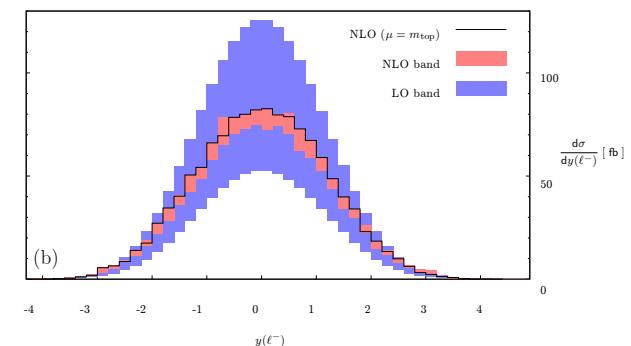
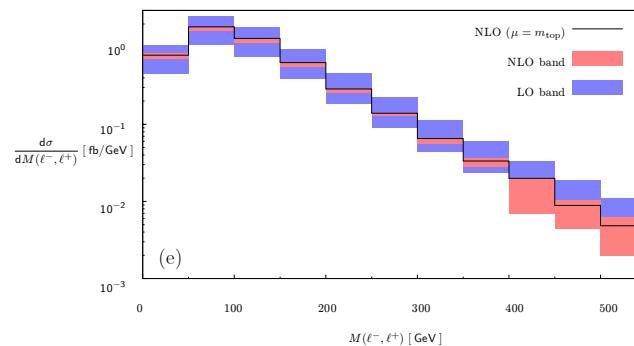
# Process: $t\bar{t} + \text{jet}$

We include LO decays into leptons and jets:

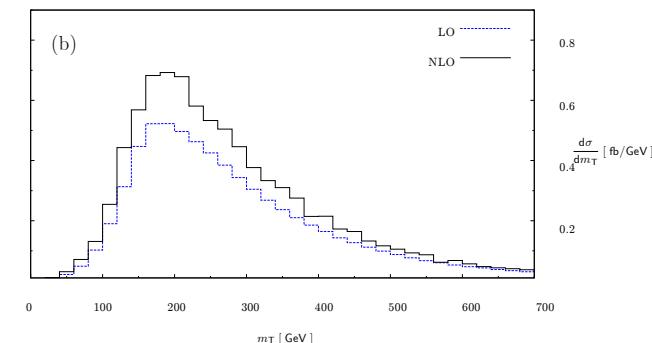
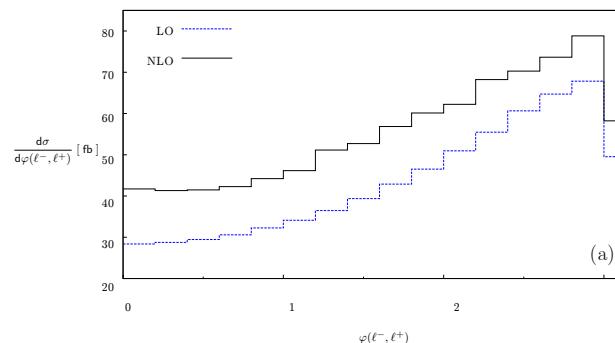
Tevatron:  
(semi-lept.)



LHC, signal:  
(7 TeV, di-lept.)



LHC, VBF bkgrd.:  
(14 TeV, di-lept.)



**Process:**  $t\bar{t}$  + jet

Runtime

Virtual corrections:  $gg \rightarrow t\bar{t}g$        $5000\text{min}/0.65\text{Mevents} = 460\text{msec/event}$

( Intel Xeon 2.8GHz,  
events after cuts,  
incl. QuadPrec stabilization )

Real corrections:  $gg \rightarrow t\bar{t}gg$        $2400\text{min}/7\text{Mevents} = 21\text{msec/event}$

( Intel Xeon 2.8GHz,  
events after cuts,  
 $\alpha = 10^{-2}$  )

with a handful of quad-core processors  $\Rightarrow$  distributions in 4 days

DWU:  $\approx 10\times$  faster for virtual corrections.

However, we compare an analytic reduction with a fully numerical approach.

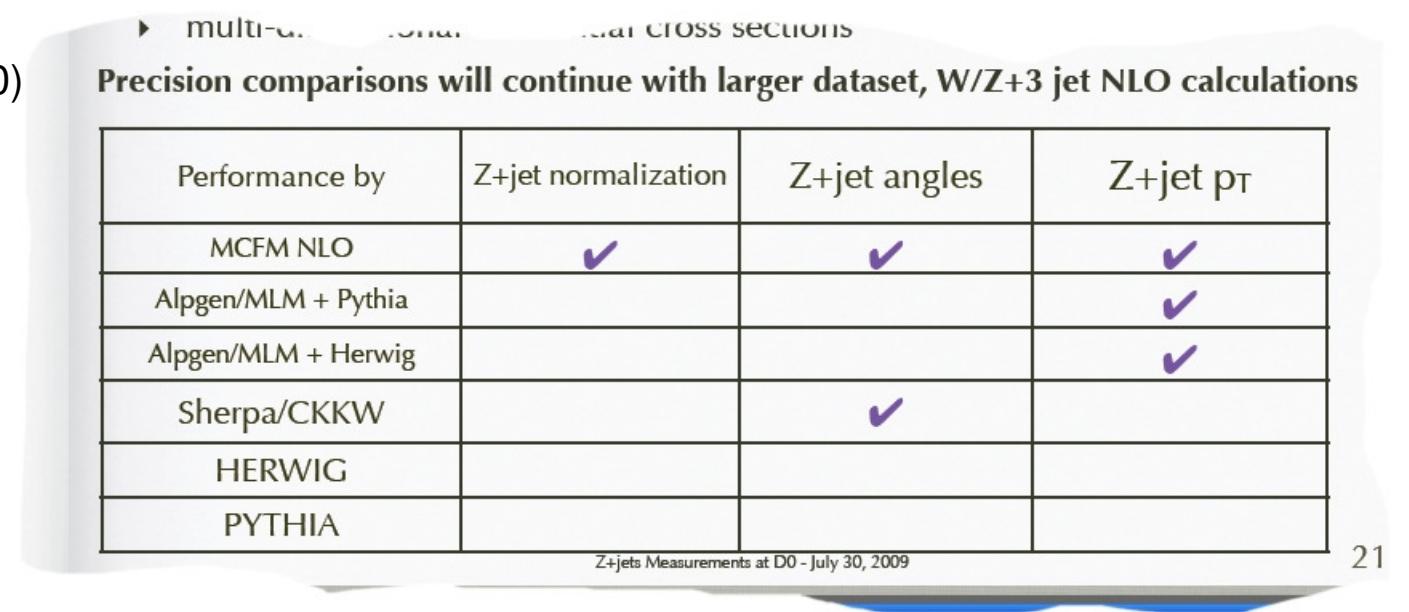
# Summary

- NLO QCD corrections to  $t\bar{t}$  production and decay
  - D-dimensional generalized unitarity + OPP
  - realistic description of the final state
- Required for precision measurements at the LHC (total cross section, top mass, spin correlations)
- NLO QCD corrections to  $t\bar{t} + \text{jet}$  production
  - method works well for a complex process
  - discrimination of background & Higgs signals requires a realistic description of the final state

# Extras

## Sabine Lammers (U-Indiana, D0)

comparison of different MC generators with D0 data for Z+jet (Run II, 1fb-1 )



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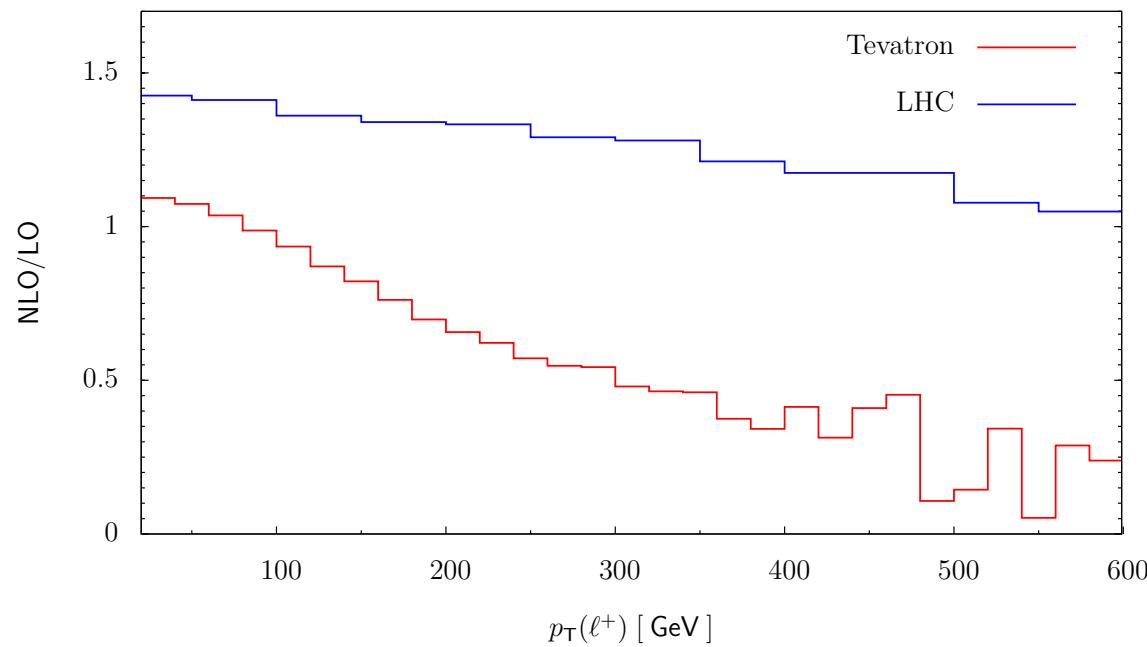
→ If precise measurements are available, NLO describes data best.

$Z + \text{jet}$  at Tevatron  $\sim t\bar{t}$  at LHC

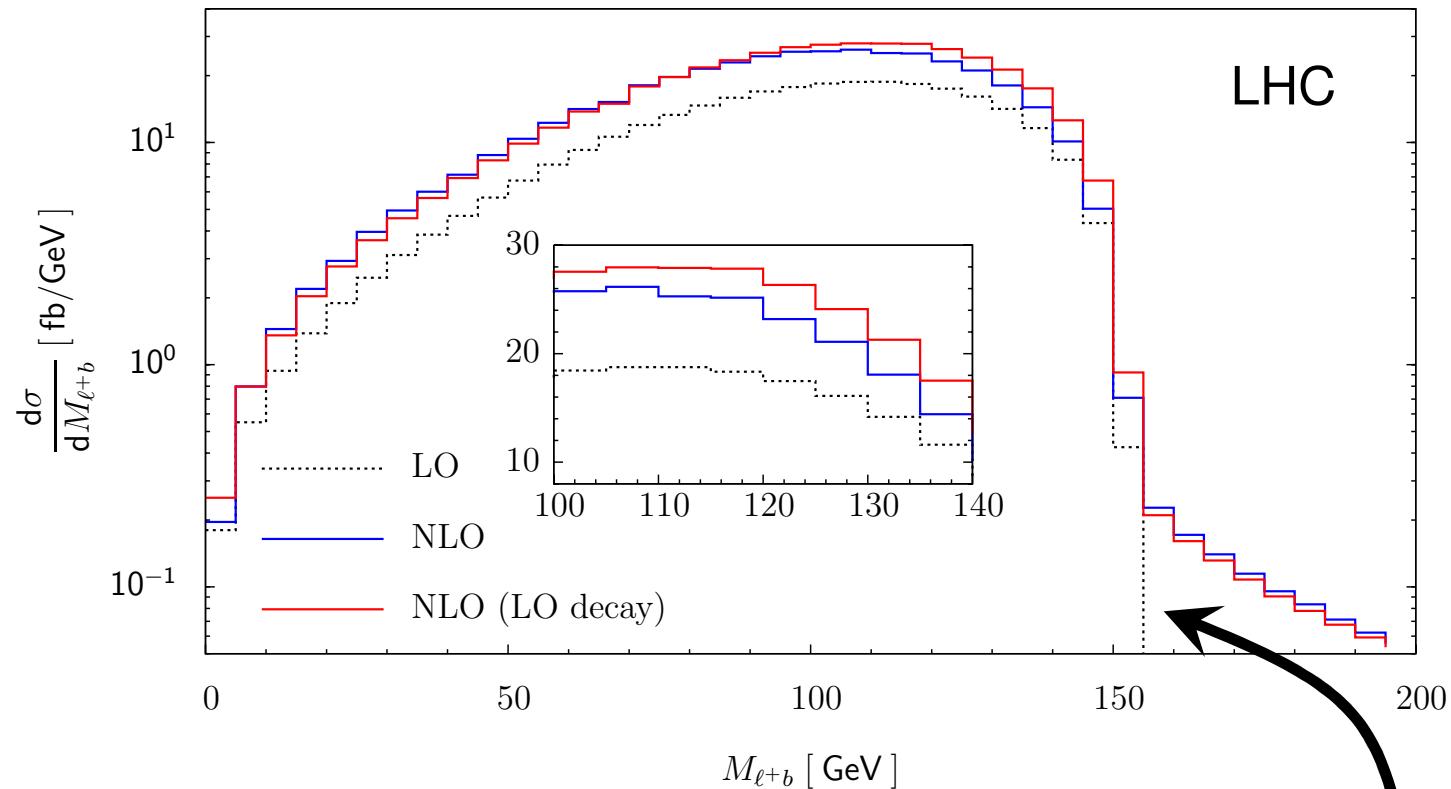
TEV  $\rightarrow \mathcal{O}(1000)$  events

LHC  $\rightarrow \mathcal{O}(10000)$  events already with 1/fb

## K - factor



## invariant mass of lepton and b-jet



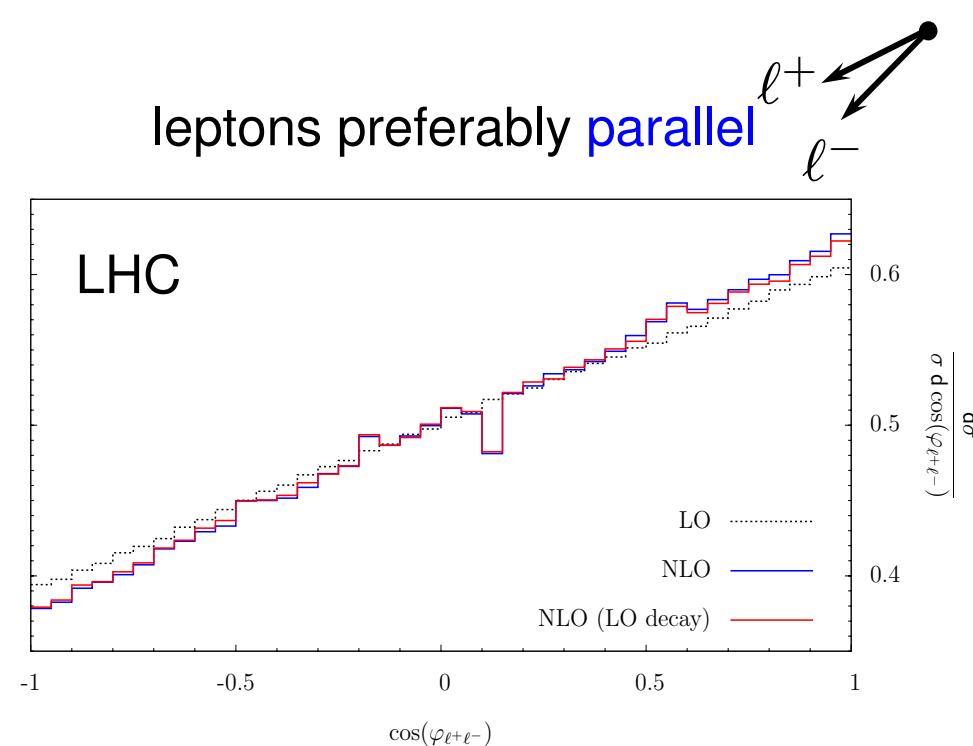
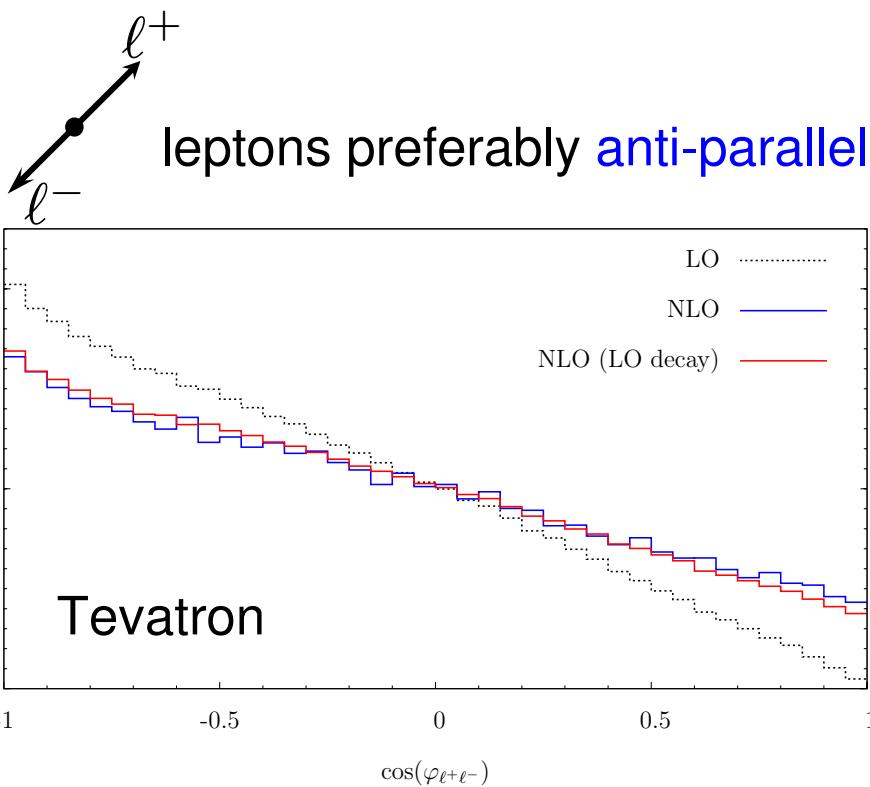
- boundary is top mass dependent
- spin studies for BSM particles
- NLO induces a tail

$$\max(M_{\ell+b}^2) = m_{\text{top}}^2 - m_W^2$$

*typical observable:*

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos(\varphi_{\ell^+ \ell^-})}$$

$\varphi_{\ell^+ \ell^-}$ : angle between the directions of flight of leptons in the corresponding ***top rest frame***

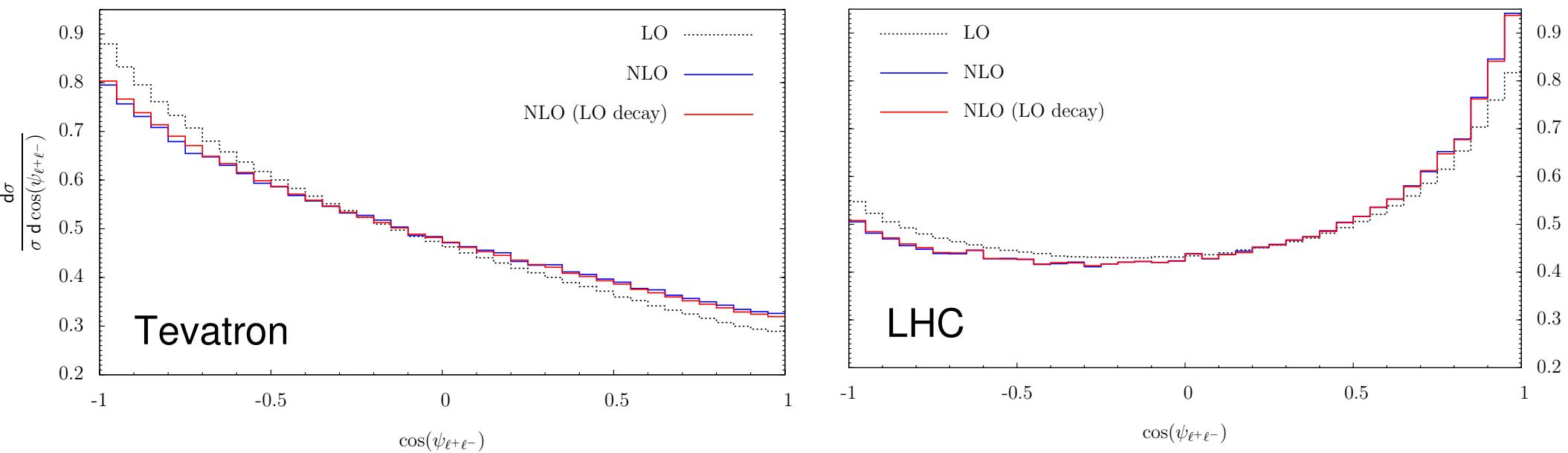


- substantial angular correlations, even at NLO
- NLO effects at Tevatron are significant

simpler observable:

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos(\psi_{\ell^+\ell^-})}$$

$\psi_{\ell^+\ell^-}$ : opening angle of the leptons in the **laboratory frame**



- top quark rest frames need not to be reconstructed
- angular correlations remain, stronger NLO effects at LHC